REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
11-03-2014	Journal Article	

4. TITLE AND SUBTITLE
Bioluminescence Potential Modeling and Forecasting

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)
Igor Shulman, Bradley Penta, Mark A. Moline, Stephanie Cayula, Matthew Oliver, Steven H.D. Haddock, Peter Sakalaukus and Alan Weidemann

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-4877-03-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PU/7330--13-1787

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Bioluminescence in the ocean is the result of light produced by a chemical reaction within organisms. There is a long documented history of brilliant displays of bioluminescence in the wakes of ships, breaking waves, around the bodies of rapidly moving fish and mammals, and from simple agitation of the water with one's hand or a stick. Predictions of the location, timing and intensity of bioluminescence (BL) potential and intensity of bioluminescence water leaving radiance (BLw) are critical for numerous naval operations, including preventing detection of covert operations, as well as in aiding detection of enemy incursions. Risks and opportunities from bioluminescence radiance directly depend on the Inherent Optical Properties (IOPs), as the propagation of BL radiance depends on the optical properties of the water. Therefore, joint modeling and predictions of BL potential and IOPs are very important for Navy objectives. Combining predictions from physical, bio-optical and bioluminescence models, a methodology for stimating the BL potential and night time water leaving radiance is demonstrated and evaluated. Modeling and data assimilation with nested, coupled physical, bio-optical models are computationally-demanding, and realistic, high-resolution simulations cannot be performed without the resources.

15. SUBJECT TERMS
Bioluminescence; ocean modeling, ocean forecasting

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU	04	Igor Shulman
					19b. TELEPHONE NUMBER *(Include area code)* (228) 688-5646

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

13-1231-1763

PUBLICATION OR PRESENTATION RELEASE REQUEST Pubkey: 8828 NRLINST 5600.2

Ref: (a) NRL Instruction 5600.2
(b) NRL Instruction 5510.40D

Encl: (1) Two copies of subject paper (or abstract)

( ) Abstract only, published
( ) Book
( ) Conference Proceedings (refereed)
( ) Invited speaker
( ) Journal article (refereed)
( ) Oral Presentation, published
(X) Other, explain

( ) Abstract only, not published
( ) Book chapter
(X) Conference Proceedings (not refereed)
( ) Multimedia report
( ) Journal article (not refereed)
( ) Oral Presentation, not published

STRN NRL/PU/7330-13-1787
Route Sheet No. 7330/
Job Order No. 73-4877-03-5
Classification X U C
Sponsor ONR
approval obtained ___ yes X no

Title of Paper or Presentation
Bioluminescence Potential Modeling and Forecasting

Author(s) Name(s) *(First,MI,Last), Code, Affiliation if not NRL*

Igor G. Shulman 7331 **Bradley Penta** 7331 **M.A. Moline** Univ. of Delaware **Stephanie C Cayula** 7331 **Matt Oliver** University of Delaware **S. Haddock** Monterey Bay Aquarium Research Inst. **Peter Sakalaukus** 7331 **Alan D. Weidemann** 7333

It is intended to offer this paper to the ______________________
(Name of Conference)

____
(Date, Place and Classification of Conference)

and/or for publication in **2013 HPC DoD Mission Succcess Book, Unclassified** ______________
(Name and Classification of Publication) *(Name of Publisher)*

After presentation or publication, pertinent publication/presentation data will be entered in the publications data base, in accordance with reference (a).
It is the opinion of the author that the subject paper (is ____) (is not __X__) classified, in accordance with reference (b).
This paper does not violate any disclosure of trade secrets or suggestions of outside individuals or concerns which have been communicated to the Laboratory in confidence. This paper (does ____) (does not __X__) contain any militarily critical technology.
This subject paper (has ____) (has never __X__) been incorporated in an official NRL Report.

Igor G. Shulman, 7331 ______________________
Name and Code *(Principal Author)* (Signature)

CODE	SIGNATURE	DATE	COMMENTS
Author(s) Shulman	[signature]	5/22/2013	Need by 07 Jun 13
			Publicly accessible sources used for this publication
			This is a Final Security Review. ~~Any changes made in the document, after approved by Code 1231,~~ nullify the Security Review.
Section Head Gould	RW Gould	5/22/13	
Branch Head Richard L. Crout, 7330	[signature]	5/22/2013	
Division Head Ruth H. Preller, 7300	Ruth H Preller	5/22/13	1. Release of this paper is approved. 2. To the best knowledge of this Division, the subject matter of this paper (has ____) (has never __X__) been classified.
Security, Code 1231	[signature]	5/22/13	1. Paper or abstract was released. 2. A copy is filed in this office.
Office of Counsel, Code 1008.3	Kathy Chapman	5/24/13	
ADOR/Director NCST E. R. Franchi, 7000			
Public Affairs *(Unclassified/ Limited Only)*, Code 7030.4	Shannon Mensi	5-23-13	22 MAY '13 PM3:45
Division, Code			
Author, Code			

NRL 5511/6 (Rev. 12-98) (e) THIS FORM CANCELS AND SUPERSEDES ALL PREVIOUS VERSIONS

05/23/2013 10:43 2027679046 PAGE 03/04

Bioluminescence Potential Modeling and Forecasting

Igor Shulman (1), Bradley Penta (1), Mark A. Moline (2), Stephanie Cayula(1), Matthew Oliver (2),
Steven H.D. Haddock (3), Peter Sakalaukus (1) and Alan Weidemann (1)

(1)Oceanography Division, Naval Research Laboratory, Stennis Space Center, MS
(2)University of Delaware, Lewes, Delaware, USA
(3)Monterey Bay Aquarium Research Institute, Moss Landing, CA

Abstract

Bioluminescence in the ocean is the result of light produced by a chemical reaction within organisms. There is a long documented history of brilliant displays of bioluminescence in the wakes of ships, breaking waves, around the bodies of rapidly moving fish and mammals, and from simple agitation of the water with one's hand or a stick. Predictions of the location, timing and intensity of bioluminescence (BL) potential and intensity of bioluminescence water leaving radiance (BLw) are critical for numerous naval operations, including preventing detection of covert operations, as well as in aiding detection of enemy incursions. Risks and opportunities from bioluminescence radiance directly depend on the Inherent Optical Properties (IOPs), as the propagation of BL radiance depends on the optical properties of the water. Therefore, joint modeling and predictions of BL potential and IOPs are very important for Navy objectives. Combining predictions from physical, bio-optical and bioluminescence models, a methodology for estimating the BL potential and night time water leaving radiance is demonstrated and evaluated. Modeling and data assimilation with nested, coupled physical, bio-optical models are computationally-demanding, and realistic, high-resolution simulations cannot be performed without the resources provided by the High Performance Computing Modernization Program (HPCMP).

Background

Dinoflagellates are responsible for 70-90% of the bioluminescent signal in coastal planktonic systems. However, it is produced by many types of organisms from bacteria to fish and even a few sharks. Most bioluminescent organisms in the marine environment generate light in response to mechanical stimulation. This mechanically stimulated bioluminescence is called bioluminescence (BL) potential. The BL potential is measured as the flash potential from a single stimulus event in a chambered pump-through bathyphotometer.

The development of the BL potential forecasting capability has been illusive due to the complexity of factors contributing to the presence and growth of bioluminescent organisms. Bioluminescent plankton have a diversity of mobility and size, and they consist of a mix of trophic levels from bacteria to fish. With new advancements in AUV instrumentation, BL potential observations are now routinely collected together with other bio-optical and physical observations by many ocean observing systems in the U.S. and throughout the world. It is recognized that BL potential observations, in combination with bio-optical and physical observations, provide valuable insight into ecosystem health and dynamics. Increased BL observational programs provide new and improved opportunities for BL potential model development and initialization, as well as for the initialization of coupled bio-optical and physical models. All of these recent scientific advancements now allow us to address the fundamental research questions and issues related to the development of the BL potential forecasting capability. Present Navy predictive capabilities of BL potential, however, are limited to climatology with no capability for short-term predictions of BL potential and BLw.

Objectives

Our objectives are to advance the forecasting of short-term (1 - 5 days) temporal and spatial changes in coastal bioluminescence potential, develop the methodology for short-term bioluminescence potential and water leaving radiance predictions, and to better understand the coupled bio-optical and physical processes in the coastal zone that governs the variability and predictability of bioluminescence potential.

Methods

The approach is based on joint studies of the BL potential and IOPs over relevant time and space scales. Dynamical, biochemical, physical and BL potential models are combined into a methodology for estimating BL potential and BLw. The physical model is based on the Navy Coastal Ocean Model (NCOM, Barron et al., 2006). For the assimilation of physical observations (temperature and salinity), the NCOM model uses the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2006). The biochemical model (the Carbon, Silicon, Nitrogen Ecosystem (CoSINE) model, Chai et al., 2002, Shulman et al., 2011) simulates the dynamics of two sizes of phytoplankton, small phytoplankton cells (< 5 μm in diameter) and diatoms, two zooplankton grazers, nitrate, silicate, ammonium, and two detritus pools. Phytoplankton photosynthesis in the biochemical model is driven by Photosynthetically Active Radiation (PAR), which is estimated based on the shortwave radiation flux from the Coupled Ocean and Atmospheric Mesoscale Prediction System (COAMPS® (Doyle et al., 2009). The Penta et al. (2008) scheme is used for PAR attenuation with depth. Constituents from the biochemical model are used to estimate chlorophyll and Inherent Optical Properties (IOPs) based on the methodology outlined by Fujii et al. (2007). For the assimilation of bio-optical observations, the reduced-order Kalman filter is used, the forecast error covariance is specified in the subspace of the multivariate (bio-optical, physical) empirical orthogonal functions (EOFs) (Shulman et al., 2013).

The BL potential model is based on the advection-diffusion-source model, with velocities and diffusivities taken from the physical model (Shulman et al., 2011, 2012). If the intensity of the light from the stimulated BL potential and IOPs is known, the propagation of the light to the surface can be estimated with the radiative transfer models. However, the use of these models with the coupled, biochemical, physical, nested, data assimilative models are computationally expensive. In the present study we estimated the propagation of light from the BL source to the surface by inverting the Penta et al. (2008) scheme, which is used in the biochemical model for attenuating the PAR with the depth.

Over the past decade, comprehensive field studies of bioluminescence have been conducted in Monterey Bay, CA. Some field programs were specifically focused on bioluminescence sampling, when BL was measured with multiple platforms including AUVs, profilers and ships. Concurrent measurements of physical, chemical and optical properties of the water, and enumerations of zooplankton and phytoplankton, were obtained. These bioluminescence observations together with coupled physical, bio-optical and bioluminescence potential models (described above) are the foundation of the approach to examine our objectives and research issues. The approach and its elements are shown schematically in Figure 1.

We design predictive experiments when the model is initialized by using a set of BL potential observations. After that we conduct forward in time simulations without assimilation of new observations; in this case the experiments simulate the forecasting of the BL potential. The forecasts are compared to the non-assimilated observations. Bio-optical, physical observations are being used also for verification and interpretation of our numerical experiments results.

Results

In the upwelling-driven system of Monterey Bay, CA, observations and model simulations showed that the offshore water masses with the subsurface layer of bioluminescent zooplankton were replaced by water masses advected from the northern coast of the bay with a relatively high presence of mostly non-bioluminescent phytoplankton (Shulman et al., 2011).

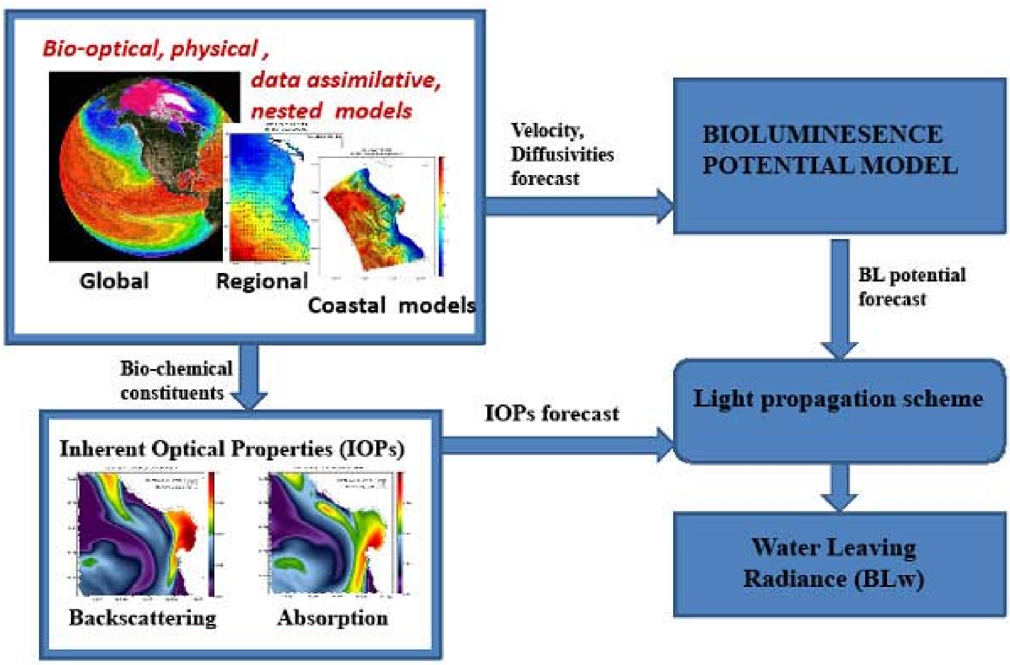

Figure 1. Approach for BL potential and BLw predictions; combining BL potential and coupled bio-optical, physical model predictions.

Offshore observations show a deeper BL potential maximum below the surface layers of high chlorophyll and backscatter values during the earlier stages of upwelling development. Later, the observed deep offshore BL potential maximum disappeared and became a shallower and much weaker signal. These dynamics influenced not only the BL potential in the region, but also the Inherent Optical Properties. By combining dynamical, predictive physical, biochemical and bioluminescence potential models, we were able to produce one of the first pictures of BLw for the entire region, illustrating the non-linearity of the quantity and the ocean circulation that, for the two components, is critical for estimation of BLw on this scale (Fig. 2).

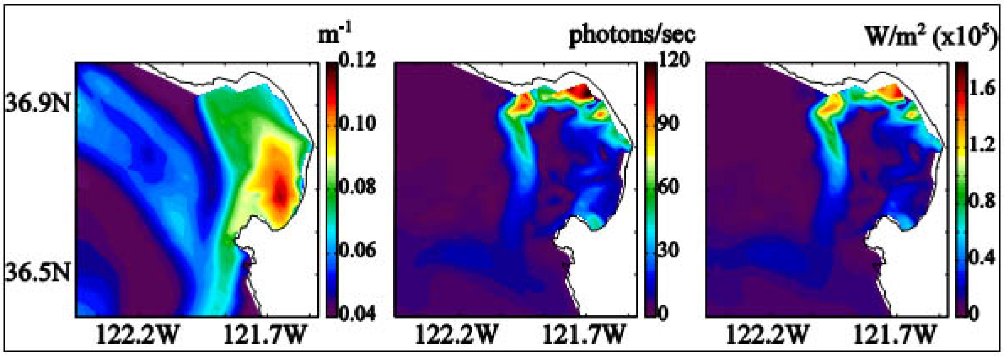

Figure 2. Water-leaving radiance at the surface due to stimulation of the modeled BL potential at 5m depth (right panel). The modeled BL potential at 5m depth (middle panel), and a sum of a (absorption) and bb (backscattering) averaged from the depth of BL potential stimulation (5m) to the surface (left panel).

Observations showed that during the upwelling, bioluminescent dinoflagellates from the northern part of the Bay were able to avoid advection by strong southward currents developed during the upwelling event. In Shulman et al., 2012, we tested the hypothesis that vertical swimming behavior explains the observed ability of dinoflagellates to avoid advection by strong currents. Three swimming behaviors were considered: sinking, swimming to the target depth and diel vertical migration (DVM). Results demonstrated that through swimming behavior, dinoflagellates avoid complete advection out of the Bay during upwelling events (Shulman et al., 2012). With a modeled swimming velocity of 20m/day (a reasonable estimate at half the observed maximum) 40 percent of the dinoflagellates population was advected from the northern part of the Bay compared to no swimming. This is in agreement with the observed mean BP ratio of 0.45 at the Bay entrance compared to the northern part of the Bay.

Concluding Remarks

Application of bioluminescence mitigation techniques requires some knowledge of the bioluminescence potential that must be reduced to minimize vulnerability to surveillance assets. Our research takes advantage of opportunity afforded by recent advances in BL potential modeling, theory and observational capabilities. Together, these advances will enable a real-time monitoring and forecast capability for assessing how Navy operations will be influenced and improved by knowledge of the BL potential along coastal zones. Continued modeling efforts such as these will gauge the measure of bioluminescence as a tool for integrating ecosystem information, evaluate dynamical optical properties in the ocean, and help in short-term prediction of oceanographic conditions, including bioluminescence potential and water-leaving radiance. Modeling and data assimilation with nested, coupled physical, bio-optical models are computationally demanding. Realistic, high-resolution simulations cannot be performed without the resources provided by the High Performance Computing Modernization Program (HPCMP).

Acknowledgements

This research was funded by the Naval Research Laboratory (NRL) and by the Office of Naval Research, Marine Mammals and Biology Program. Computer time for the numerical simulations was provided through a grant from the Department of Defense High Performance Computing Initiative. This manuscript is NRL contribution #7330-13-1787.

References

Barron, C. N., A. B. Kara, P. J. Martin, R. C. Rhodes, and L. F. Smedstad, 2006: Formulation, implementation and examination of vertical coordinate choices in the global Navy Coastal Ocean Model (NCOM). Ocean Modelling, 11, 347-375, doi:10.1016/j.ocemod.2005.01.004.

F. Chai, R.C. Dugdale, T.-H. Peng, F.P. Wilkerson, and R.T. Barber, 2002 "One-dimensional ecosystem model of the equatorial Pacific upwelling system. Part I: model development and silicon and nitrogen cycle," Deep Sea Res. II 49, 2713-2745.

Cummings, J. A., 2006: Operational multivariate ocean data assimilation, Q. J. R. Meteorol. Soc. (2005), 131, pp. 3583-3604

Doyle J. D., Q. Jiang, Y. Chao, J. Farrara, 2008. High-Resolution Atmospheric Modeling over the Monterey Bay in Support of the AOSNII Field Campaign, Deep Sea Res. II, 56 (3-5), 87-99.

Fujii, M., E. Boss, and F. Chai, 2007: The value of adding optics to ecosystem models: a case study. Biogeosci. 4, 817-835.

Penta, B., Z. Lee, R. Kudela, S. Palacios, D. Gray, J. Jolliff, and I. Shulman, 2008. An Underwater Light Attenuation Scheme for Marine Ecosystem Models. Optics Express 16, pp. 16581-16591.

Shulman, I, S. Frolov, S. Anderson, B. Penta, R. Gould, P. Sakalaukus, S. Ladner, 2013. Impact of bio-optical data assimilation on short-term coupled physical, bio-optical model predictions, J. Geophys. Res., 118, 2215-2230, doi:10.1002/jgrc.20177, 2013.

Shulman, I., B. Penta, M. A. Moline, S. H. D. Haddock , S. Anderson, M. Oliver, and Peter Sakalaukus (2012), Can vertical migrations of dinoflagellates explain observed bioluminescence patterns during an upwelling event? J. Geophys. Res.,117, C01016, doi:10.1029/2011JC007480.

Shulman, I., M. A. Moline, B. Penta, S. Anderson, M. Oliver, and S. H. D. Haddock (2011), Observed and modeled bio-optical, bioluminescent, and physical properties during a coastal upwelling event in Monterey Bay, California, J. Geophys. Res., 116, C01018, doi:10.1029/

2010JC006525.